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Development of MSL Rover Loads by ADAMS Skycrane Simulations

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# Mars Science Laboratory
The Current Mission to Mars

- Mars Science Laboratory (MSL) was successfully launched on Nov. 26, 2011
  - *Mobile Science Laboratory*
  - *One Mars year surface operational lifetime (687 days)*
  - *Discovery responsive over wide range of latitudes and altitudes*
  - *Precision landing via guided entry*
  - *Controlled propulsive landing: Skycrane Touchdown Maneuver*
  - *Mission science will focus on Mars habitability*
- Acknowledgement: Thank the many team members (Tom Rivellini, Jeff Umland, Chris White, George Antoun, Walter Tsuha, Steve Sell, Gurkirpal Singh, Linh Phan, Paul Brugarolas, Alejandro San Martin, etc.) who have supported and contributed to this work.
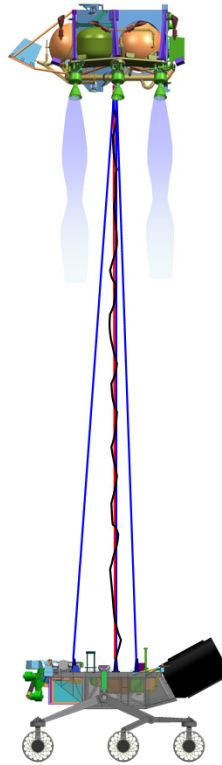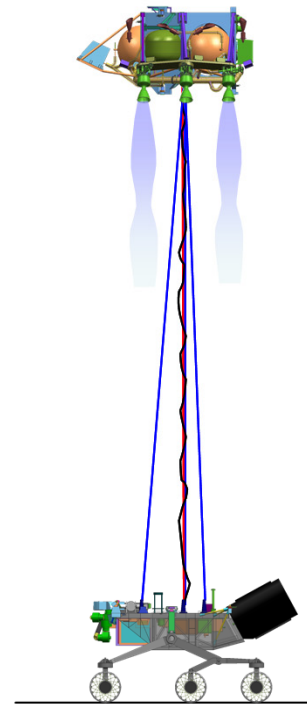
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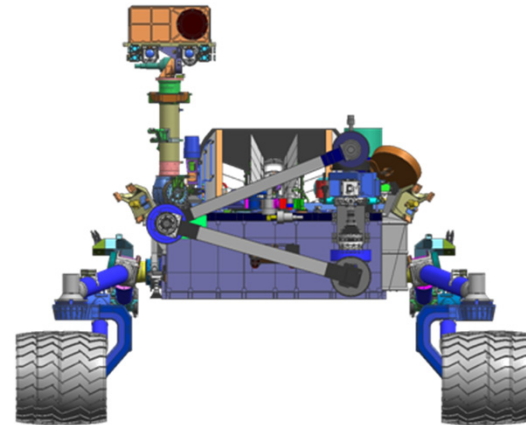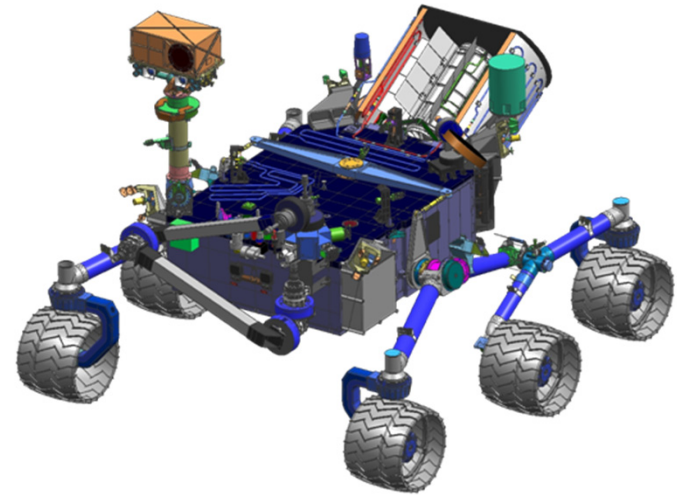
Skycrane Touchdown Maneuver
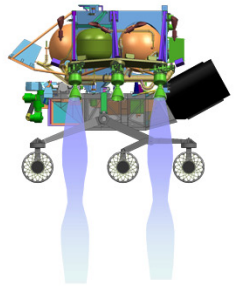
One Body Phase
(Vertical Descent)
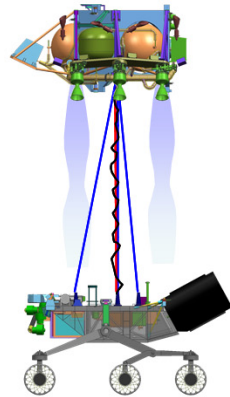
Two Body Phase
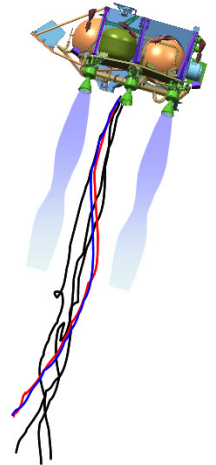**(DRL/Bridle Deployment)**

Two Body Phase
(Constant Velocity)

Two Body Phase
(Touchdown Event)

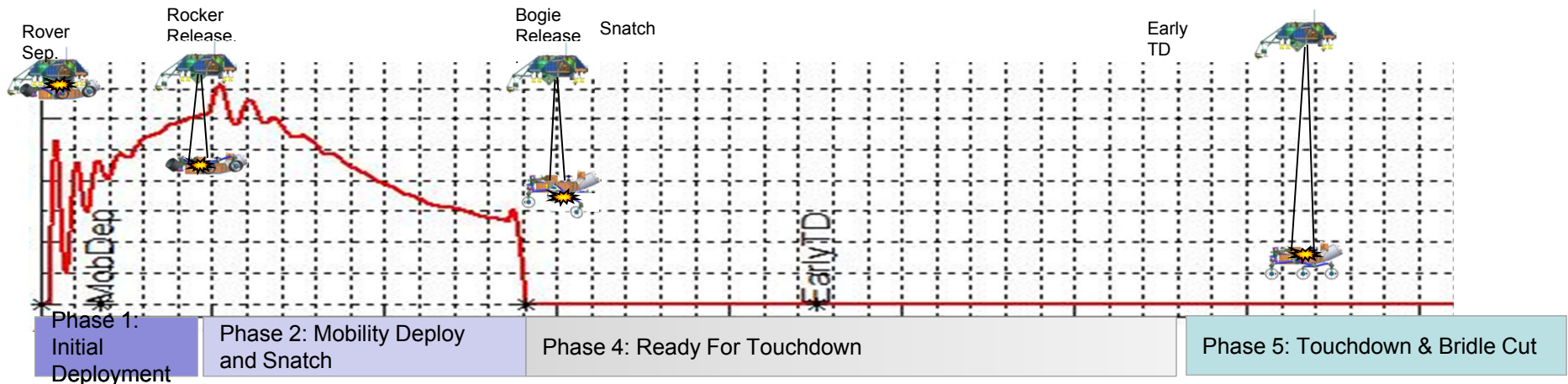**Fly-Away Phase**

Skycrane Maneuver Timeline

Rover Separation
via BUD

Mobility Deploy -
Rocker Release

(Aft: Rover Sep + 0.7s
Fwd: Rover Sep + 0.825s)

Mobility Deploy -
Bogie Release

(Rover Sep + 6.0s)

Touchdown/Bridle Cut

(Rover Sep + 9 to 17s)

ADAMS Simulation of Skycrane Maneuver

- Objectives
  - *Determine the Rover limit design loads in the mobility elements and joints*
  - *Determine the Rover limit design loads on the rigid body Rover chassis*

- Loads Analysis Methodology
  - *Develop ADAMS simulations for Rover separation, mobility deploy and touchdown*
  - *Use ADAMS transient dynamic analysis capability to generate time domain loads*
  - *Incorporate GNC flight software in ADAMS closed-loop simulations*
  - *Employ Monte Carlo approach by varying key input parameters*
  - *Apply a Model Uncertainty Factor (MUF) of 1.2*

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ADAMS Simulation of Skycrane Maneuver (cont.)

- An intensive effort has been made to develop an ADAMS simulation with the latest GNC flight software for the skycrane maneuver till touchdown.

  - *Powered Descent ← 55m above ground, (V_h, V_v)= (0,20) m/s*

  - *Throttle Down*

  - *Rover Separation → PDV States at Rover Sep, Clearance Check*

  - *Mobility Deploy → Verification Mobility Deploy Loads*

  - *Ready for Touchdown → Ready-for-Touchdown States*

  - *Touchdown →Verification Touchdown Loads*

  - *Bridle Cut → Touchdown Trigger Performance*

  - *Flyaway*

- Run on 8 CPUs of 2 HP workstations with 4TB institution storage

- Run stats of ADAMS skycrane simulations are listed in the following:

  - *CoF = 1.0 run time: 18 to 88 minutes, mean = 36.2 minutes*

  - *CoF = 0.5 run time: 17 to 93 minutes, mean = 35.6 minutes*

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Monte Carlo Loads Analysis Methodology

- Due to the complex dynamics during the Skycrane maneuver phases, the Rover limit design loads methodology employs the Monte Carlo simulation technique to take into account the loads uncertainty.

- Parameter values and dispersions documented with configuration control memos and tables.

- Use 500 to 2,000 Monte Carlo simulation runs to generate the Rover mobility deploy and touchdown loads at 99th percentile with a 1.2 MUF.
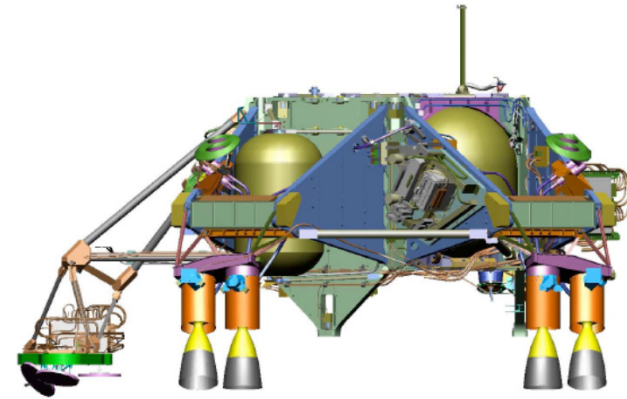
Absolute min/max Fx at wheel-1 from 2,000 runs

The rest of force/moment components from run ID

Run ID producing absolute max/min Fx at wheel-1

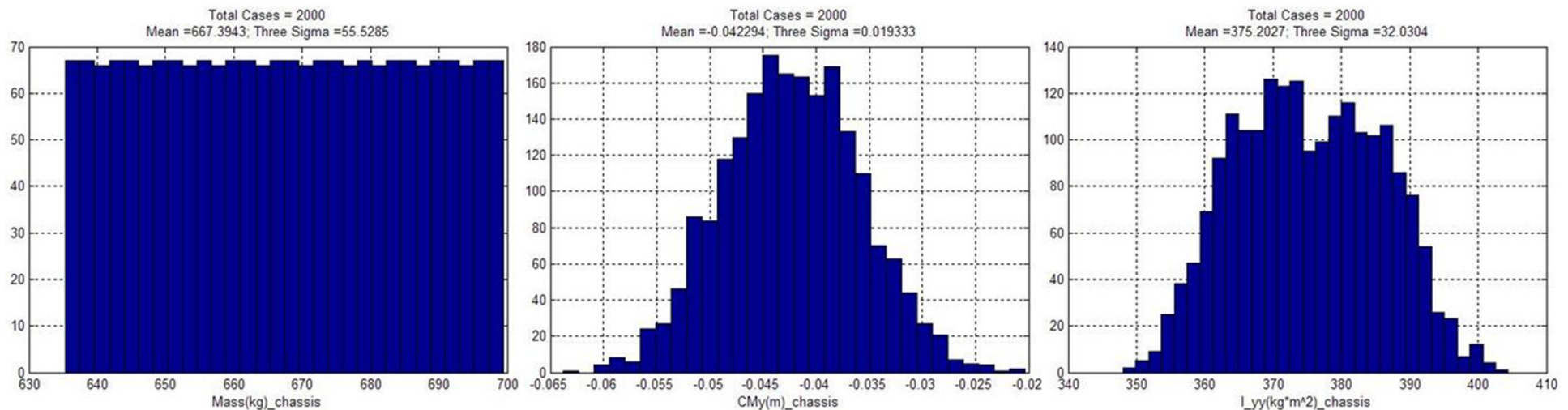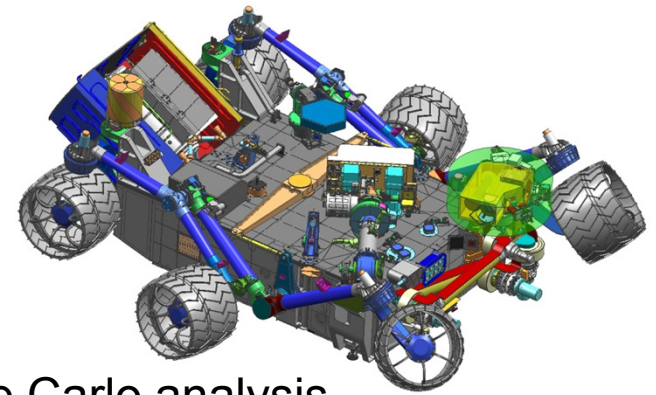| Item	FXa (N)	FYs (N)	FZs (N)	FMs (N)	MXt (N-M)	MYb (N-M)	MZb (N-M)	MMb (N-M)	RUN ID.
W1_FX (N)									
W1_FY (N)									
W1_FZ (N)									
W1_FM (N)									
W1_MX (N-M)									
W1_MY (N-M)									
W1_MZ (N-M)									
W1_MM (N-M)									
W2_FX (N)									
W2_FY (N)									
W2_FZ (N)									
W2_FM (N)									

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Descent Stage & GNC Model

- Descent Stage
  - *Modeled as rigid body*
  - *Mass properties dispersed per mass engineer's Monte Carlo analysis*
  - *MLE forces applied as external 'follower' loads*

- GNC Model
  - *Flight GNC software compiled and linked into ADAMS closed-loop sims*
  - *Assumes perfect navigation*
  - *MLE thrust variations implemented on ADAMS model side by applying a uniformly distributed thrust multipliers of [0.95, 1.05]*
  - *Velocity dispersions done on GNC module side to set touchdown velocity*
    - V_h = 0.00 ± 0.3 m/sec (normal distribution)
    - V_v = 0.75 ± 0.1 m/sec (normal distribution)
  - *Outputs key time histories and powered descent states to assess GNC touchdown trigger performance*

Rover Model

- Chassis modeled as rigid body
- Mass properties dispersed per mass engineer's Monte Carlo analysis

Total Cases = 2000
Mean =667.3943; Three Sigma =55.5285
Mass(kg)_chassis

Total Cases = 2000
Mean =-0.042294; Three Sigma =0.019333
CMy(m)_chassis

Total Cases = 2000
Mean =375.2027; Three Sigma =32.0304
I_yy(kg*m^2)_chassis

- Articulating mobility system modeled with flexible beam elements and end-of-range hardstops
- Joints incorporate nonlinear behavior due to dead zones and hardstop stiffness
- Realistic parasolid wheel (tire) model with 6x6 stiffness matrix at hub

Bridle Umbilical Device (BUD) Model

- Bridles modeled as tension only elements whose length varies per solution of BUD state equations
  - *Stiffness per bridle → Scaled by a uniformly dispersed factor of [0.45, 1.92]*
  - *Damping per bridle = 100 N/(m/sec), needed by numerical solution, resulting a very small contribution to the total force of each bridle*
  - *BUD brake coefficient → Uniformly dispersed*
  - *Uniform slack of all three bridles: [0.02, 0.04]m, uniform dispersion*
  - *Differential slack of each bridle: [-0.02, 0.02]m, uniform dispersion*

- Umbilical force modeled by a bounding "sawtooth" profile of test data

Deploy Length

Umbilical Force

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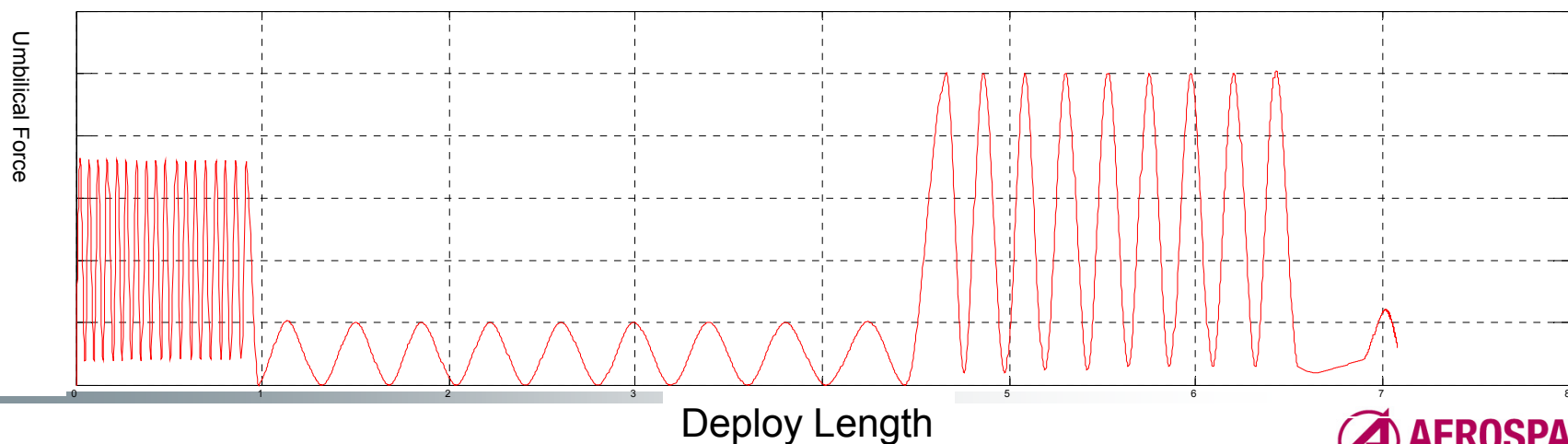
Dispersions of Mobility Deploy Parameters

- Uniform dispersions of stiffness, damping, friction and drag parameters
  - *Bogie pivot: spring stiffness, Coulomb friction, viscous damping*
  - *Rocker deploy pivot: Coulomb friction, viscous damping*
  - *Center differential pivot: spring stiffness, Coulomb friction*
  - *Main differential pivot: Coulomb friction*

- Mobility deployments captured, using dispersed release times
  - *Nominal aft rocker arm release: Rover sep + T1 sec (aligned with RTI boundaries)*
  - *Nominal fwd rocker arm release: Aft rocker arm release + T2 sec*
  - *Nominal bogie arm release: Rover Sep + T3 sec*
  - *Nominal mobility deploy times (T1, T2, T3) dispersed by the following pyro firing delays:*
    - Mobility release timings that nominally occur simultaneously (specifically the port and stbd rocker and bogie releases) shall be dispersed from a simultaneous firing per a uniform distribution of (-0,+5) msec.
    - Mobility release timings that nominally occur 0.125 msec apart (specifically the fore-aft rocker firings) shall be dispersed from the nominal value of 0.125 msec per a uniform distribution of (-5,+5) msec.

Dispersions of Slope and Rock

- Terrain slope dispersion is based on "best estimate" statistics regarding the rover-scale (2m) slope that will be encountered at two candidate landing sites.
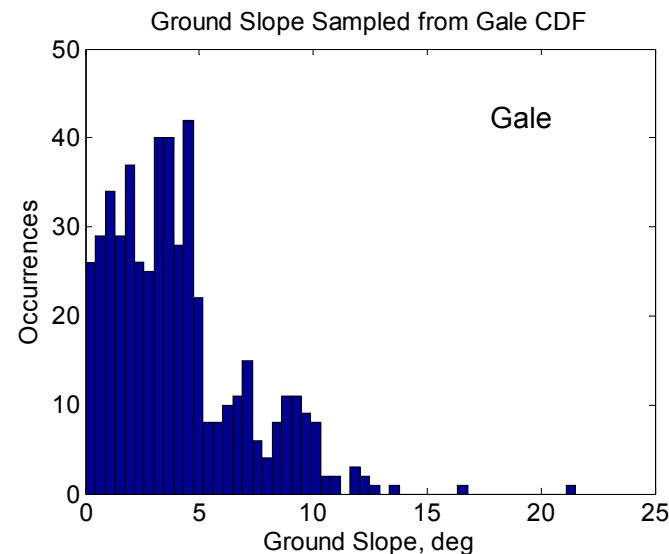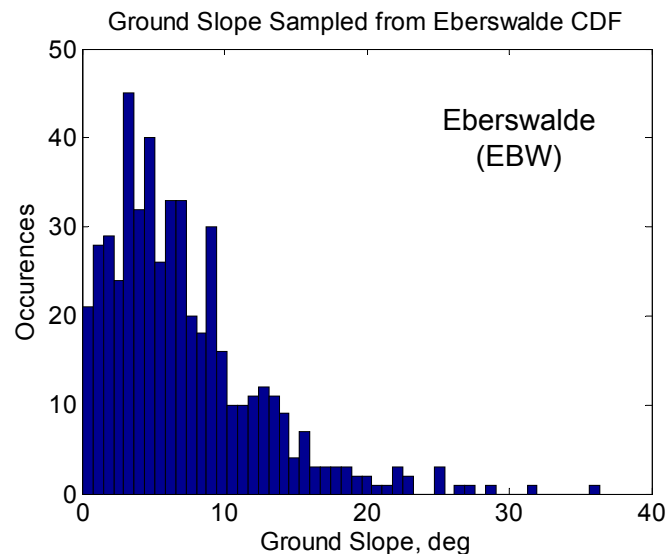

- Rock dispersion is also based on "best estimate" statistics regarding the rock distribution that will be encountered at the two candidate landing sites.

  - *Generate 20mx20m rock field with a bounding rock population of 20%.*

  - *Assume all rocks are hemispheres of discrete sizes (e.g. 30cm, 40cm, or 55cm radius).*

  - *Emplace rocks at random locations within the rock field.*

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Representative Results

Mobility Deploy Loads

- Based on the 99th percentile mobility deploy loads with a MUF of 1.2, small or negative margins were observed initially at critical locations such as center differential pivot, horizontal swing arm, vertical swing arm, bogie pivots, rocker pivots, mid-wheel restraints/hardstops, etc.
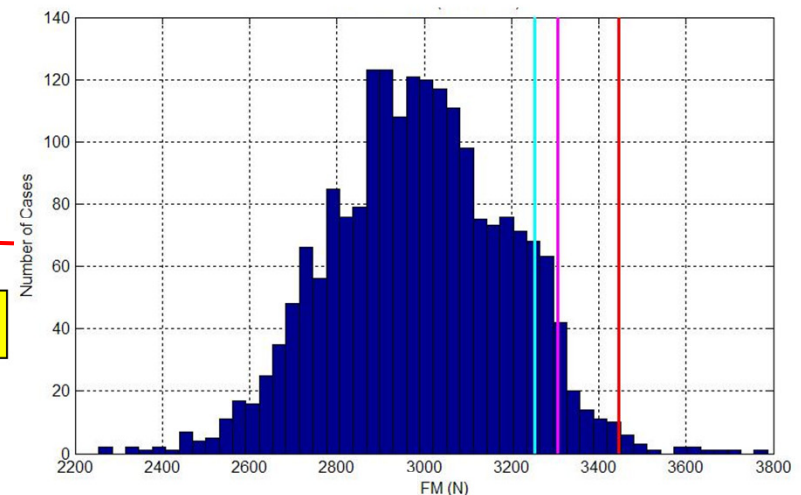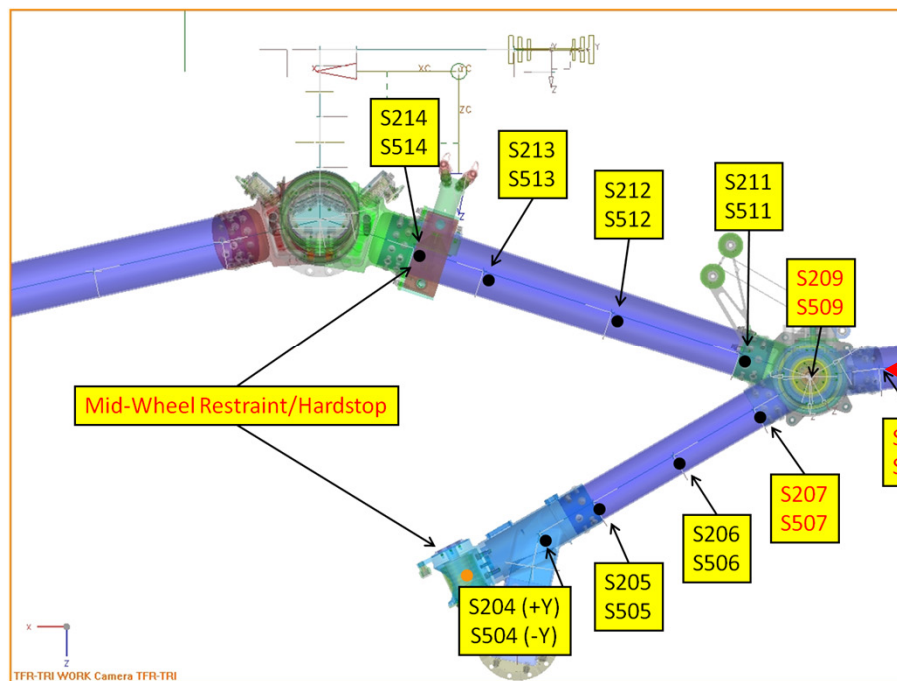

- Based on many Monte Carlo MD loads studies (with vs. without soft deploy, new vs. old MD timing, etc.), it was shown that the MD loads problem could be resolved by new MD timing without soft deploy.

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Representative Results

Bridle Umbilical Device Loads

- The following figures illustrate descent brake torque vs. angular velocity with a MUF of 1.0 from a typical set of Monte Carlo runs with new MD timing.
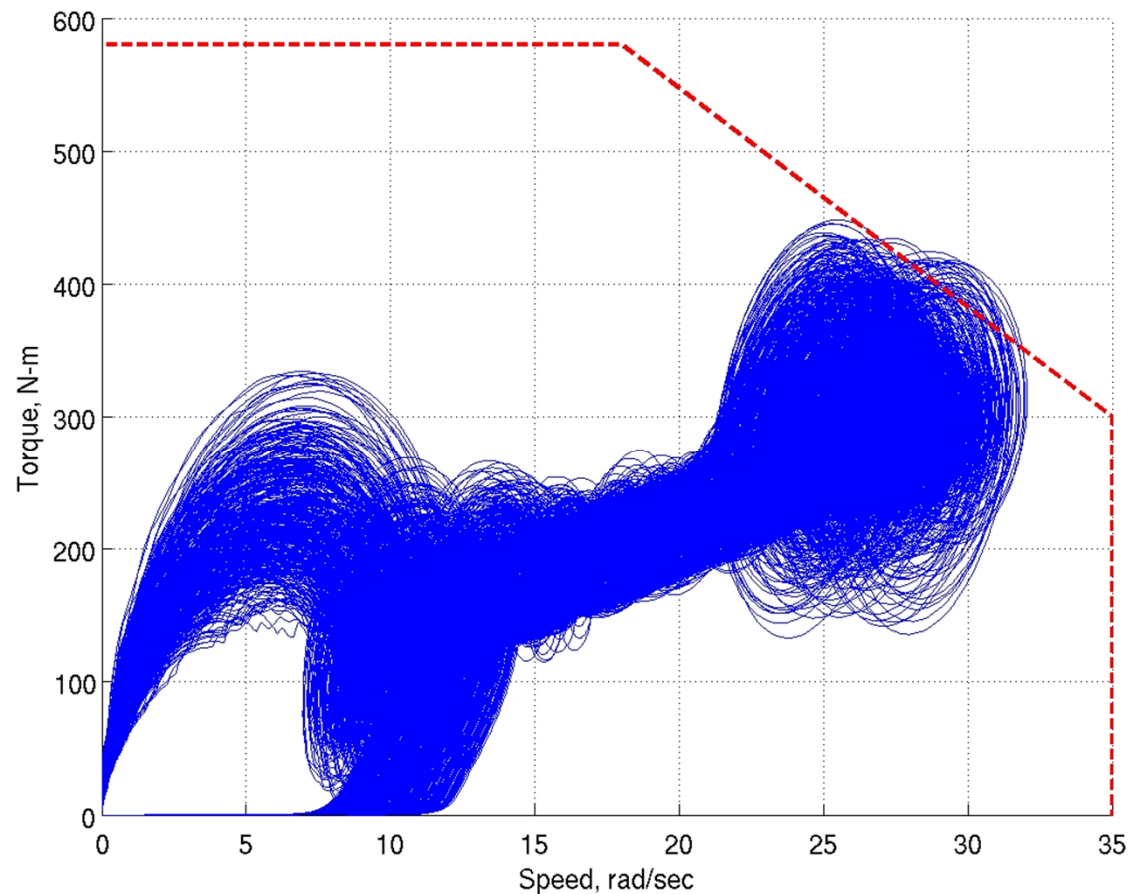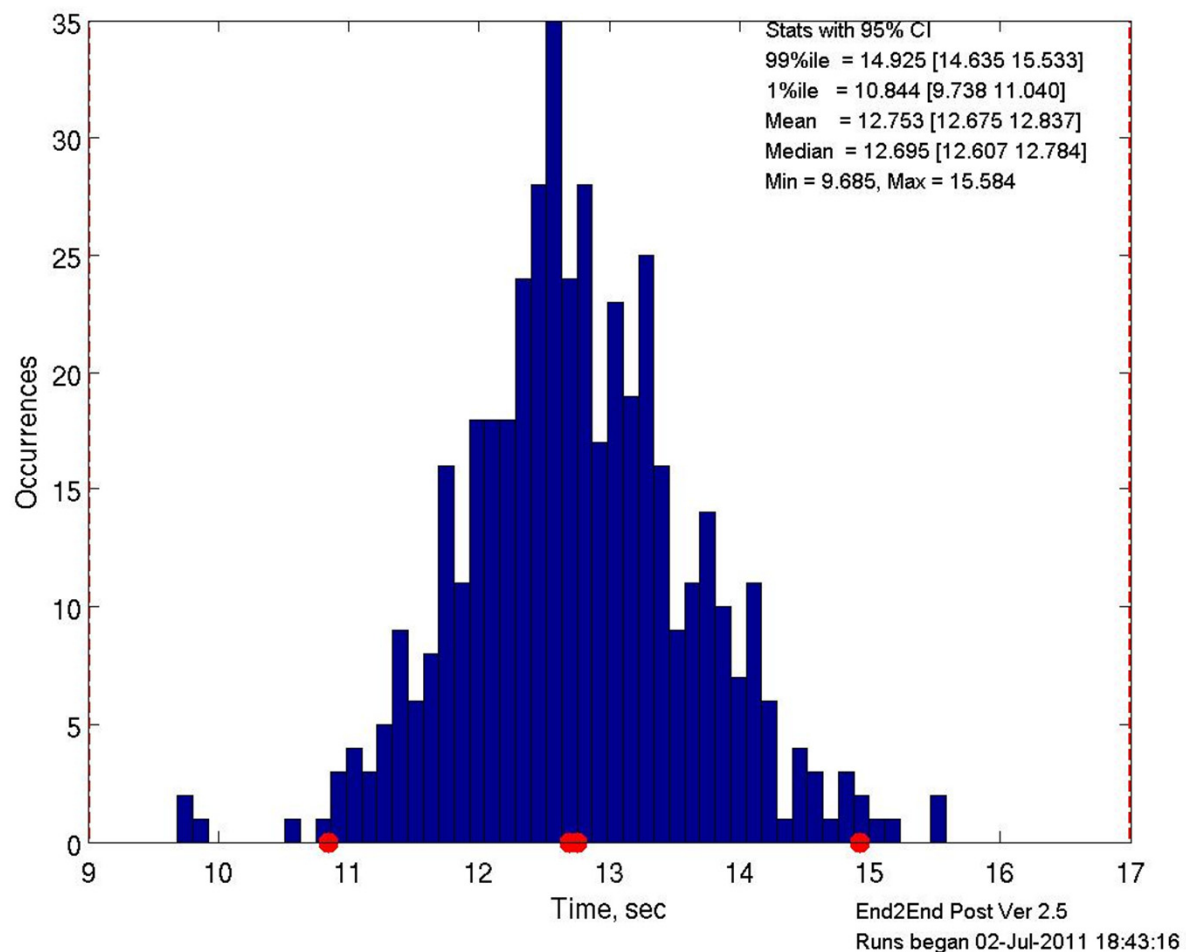

- As shown above, the descent brake loads with new MD timing are slightly outside the capability envelop (red dashed line).

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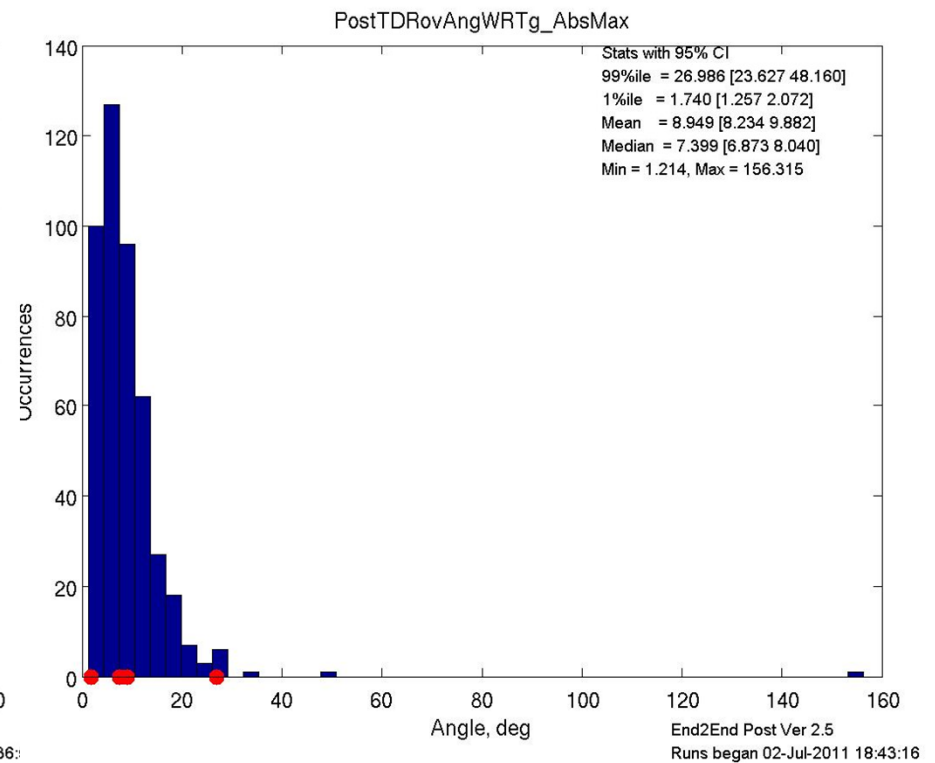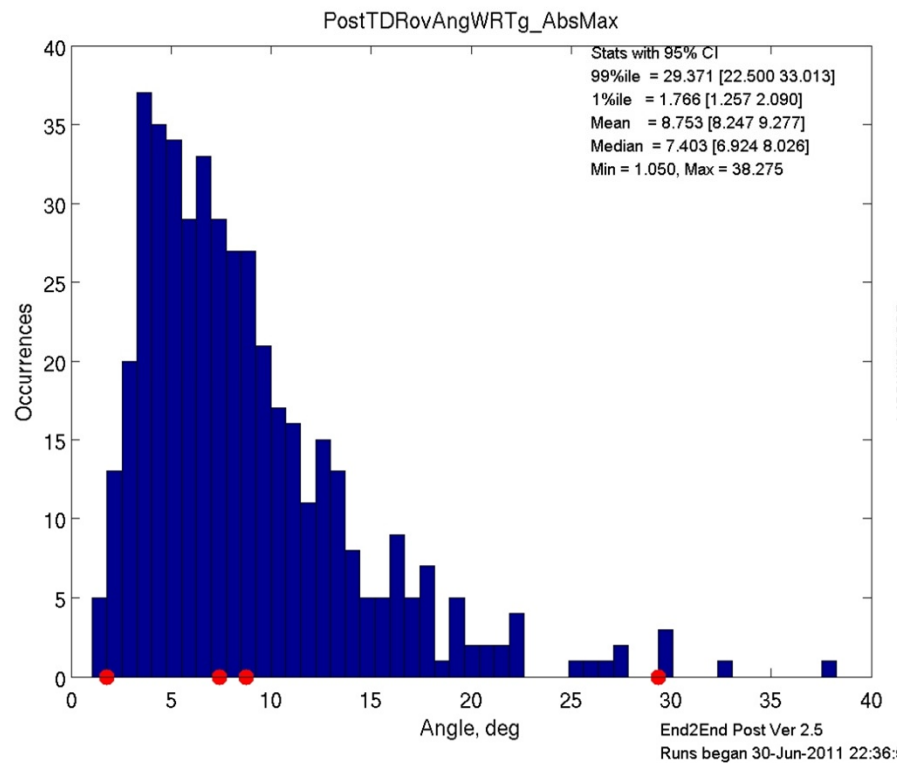# Representative Results
Touchdown First Contact Time

- [1%, 99%] = [10.8, 14.9] sec
- Note: The current touchdown window is [9, 17] sec after rover separation.
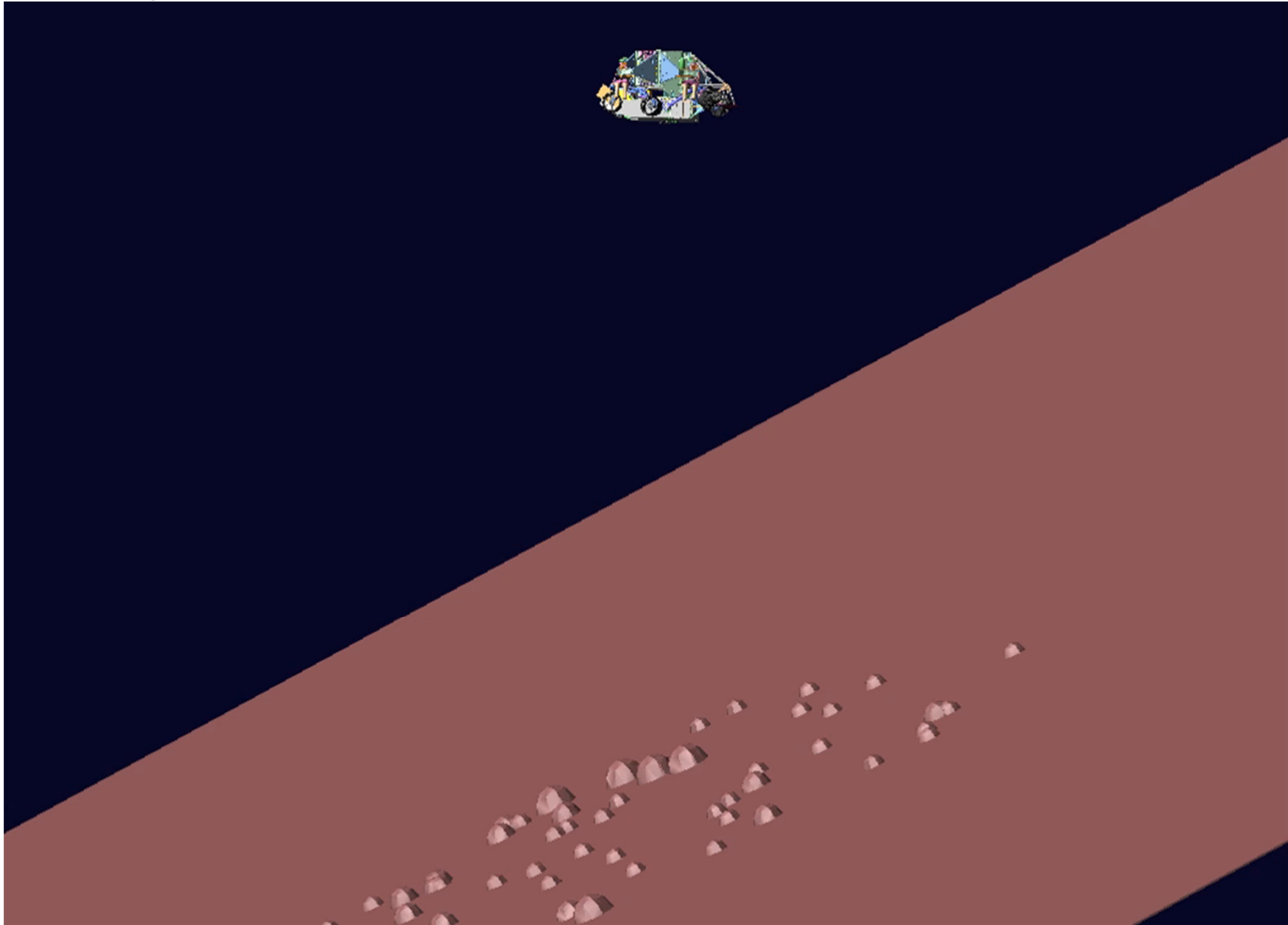
Representative Results
Rover Top Deck Angle

- CoF = 1.0 Runs: 99% Rover Top Deck Angle = 29 deg → Stability is OK
- CoF = 0.5 Runs: 99% Rover Top Deck Angle = 27 deg → Stability is OK

PostTDRovAngWRTg_AbsMax (left)

Stats with 95% CI
99%ile = 29.371 [22.500 33.013]
1%ile = 1.766 [1.257 2.090]
Mean = 8.753 [8.247 9.277]
Median = 7.403 [6.924 8.026]
Min = 1.050, Max = 38.275

End2End Post Ver 2.5
Runs began 30-Jun-2011 22:36:

PostTDRovAngWRTg_AbsMax (right)

Stats with 95% CI
99%ile = 26.986 [23.627 48.160]
1%ile = 1.740 [1.257 2.072]
Mean = 8.949 [8.234 9.882]
Median = 7.399 [6.873 8.040]
Min = 1.214, Max = 156.315

End2End Post Ver 2.5
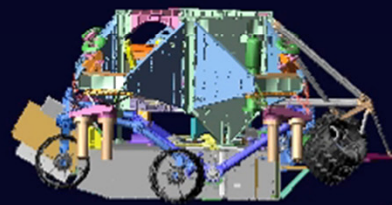Runs began 02-Jul-2011 18:43:16

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Representative Results
ADMAS Skycrane Simulation

Representative Results
ADMAS Skycrane Simulation

Conclusions

- In support of the innovative but challenging MSL skycrane system, JPL Loads Analysis and Dynamic Simulation Team has developed the ADAMS simulation capabilities for predicting the design loads and the system performance.

  - *High-fidelity ADAMS simulation capability for complicated mechanical and structural systems*

  - *Monte Carlo loads analysis capability by dispersing key input parameters*

  - *Integrated simulation capability of linking the flight GNC software directly to ADAMS closed-loop simulation*

Look forward to another successful mission to Mars!

Thank you